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Thermal Evaluation Method for Klystron RF Power

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This article examines the feasibility of adding instrumentation to the cooling system of a microwave transmitter for use as a calorimetric power measurement calibration. It considers the accuracy of the basic measurements as well as heat sources and losses not measured. Experimental results are presented in support of the theory.

I. Introduction

Figure 1 is a simplified block diagram of a transmitter, indicating the typical power measurement system. Power measured by the power meter depends on the coupling factor of the directional coupler, which typically can only be calibrated to an absolute precision of 0.5 dB or about 12%. A possible method of obtaining a more accurate absolute calibration is to measure the coolant flow to, and temperature rise across, the water load when the switch is in the water load position. By comparing the power measured in this way with the power meter reading, an in situ calibration factor can be obtained for the power meter for use when the switch is in the other position. This calibration factor includes the losses between the coupler and the switch as well as the coupler itself.

II. Dimensional Analysis

To calculate transmitter power from coolant measurements of flow rate and temperature rise, we need a K factor such that

$$\text{Power (kW)} = K \times \text{Flow (Gallons/Minute)} \times \Delta T \text{ (deg C)}$$

The dimensions of K must be (kW Minutes)/(Gallon deg C).

Handbooks and data sheets give the specific heat (Hs) of glycol mixtures in units of BTU/(lb deg F) and specific gravity (Gs) relative to water at 60 deg F as functions of percent glycol and temperature.

To reach the desired units we must go through the following chain of conversion factors:

$$K = Hs \, \frac{\text{BTU}}{\text{lb deg F}} \times Gs \, \frac{\text{g/cc}}{\text{g/cc @ 60}} \times 0.999 \text{ g/cc @ 60}$$

$$\times \frac{9 \text{ deg F}}{5 \text{ deg C}} \times 1.055 \frac{\text{kW sec}}{\text{BTU}} \times \frac{1 \text{ lb}}{453.59 \text{ g}} \times 3785 \frac{\text{cc}}{\text{gal}}$$

$$\times \frac{1 \text{ min}}{60 \text{ sec}}$$

$$K = 0.2638 \times Hs \times Gs \, \frac{\text{kW minutes}}{\text{gallon deg C}}$$

Thus to calculate the power it is necessary to know

(1) Flow rate

(2) Differential temperature

(3) Specific gravity

(4) Specific heat of the cooling fluid

The first two of these can be easily measured by a data acquisition system, but the second two are dependent on the composition of the fluid and temperature.

III. Measurement Accuracy

Volumetric Flow. A turbine flow meter for liquids can be obtained with a single point accuracy of 0.05% and linearity of 0.25% of the reading over a flow range of 10 to 1.

Temperature. Within the range of 0 to 100 deg C, a platinum RTD can be calibrated to an accuracy of ±0.03 deg C.

Fluid Density and Specific Heat. Typical cooling fluid is a mixture of deionized water with approximately 40% ethylene glycol by weight. The simplest measurement strategy is to draw a sample of the fluid, analyze it for percent glycol, and then calculate the density and specific heat. To facilitate this calculation, a multivariable, least squares curve fit produced the following expression for K, in terms of percent glycol (Pg) and degrees Celsius (Tc) which appears to be accurate to within 0.1% in the range of 20 to 40% glycol and 20 to 70 deg C:

$$K = 0.2651 - 7.048\text{e-}4\,Pg - 4.963\text{e-}6\,Pg^2$$
$$+ 5\text{e-}6\,Pg\,Tc + 6.417\text{e-}5\,Tc - 1.792\text{e-}6\,Tc^2$$

Differentiating this expression and evaluating around 40 deg C and 35 percent glycol yields:

$$(\Delta K)/K = -4.2\text{e-}3\,(\Delta Pg),$$

and

$$(\Delta K)/K = 3.1\text{e-}3\,(\Delta T)$$

Absolute accuracy of the measurement of percent glycol from a sample is around ±0.5.

Although the accuracy of an individual temperature measurement is 0.03 deg C, the fluid parameters vary with temperature through the range of ΔT. The proper solution is to integrate over temperature; however, a simpler strategy is to use the average temperature and a maximum error limit of about one fifth of the total temperature excursion, or about 2 deg C.

A. Potential Accuracy

By differentiating the log of the basic calorimetric expression it may be shown that:

$$(\Delta P)/P = (\Delta K)/K + (\Delta \text{ flow})/\text{flow} + \Delta(\Delta T)/(\Delta T)$$

Using

$$(\Delta Pg) = 1\%$$
$$(\Delta Tc) = 2 \text{ deg C}$$
$$(\Delta K)/K = 4.2\text{e-}3 \times (\Delta Pg) + 3.1\text{e-}3 \times (\Delta Tc) = 0.0104$$
$$(\Delta \text{ flow})/\text{flow} = 0.0025$$
$$(\Delta (\Delta T))/(\Delta T) = 2 \times 0.03/10 = 0.006$$

yields a potential inaccuracy of

$$(\Delta P)/P = 0.0104 + 0.0025 + 0.006$$
$$= 0.0199 \text{ or } 2\%$$

B. Other Errors

Two other limitations of the accuracy of a calorimetric power measurement are:

(1) Heat is generated in the fluid as it flows, due to viscous losses.

(2) Heat is lost to the environment due to conduction, convection and radiation, without being transferred to the cooling fluid.

1. Viscous losses. Assume a water-like liquid flowing at 11 gpm in a 1 and 1/2-in. SCH40 smooth pipe.

$$D \text{ (diameter)} = 1.61 \text{ in.}/12 \text{ in./ft} = 0.134 \text{ ft}$$
$$\bar{V} \text{ (velocity)} = 11 \text{ gpm}/6.34 \text{ gpm/fps} = 1.74 \text{ ft/s or } 6246 \text{ ft/h}$$
$$\rho \text{ (density)} = 62.4 \text{ lb}_m/\text{ft}^3$$
$$\alpha \text{ (viscosity)} = 1 \text{ cp} \times 2.42 \text{ lb}_m/\text{ft/h/cp}$$
$$= 2.42 \text{ lb/ft/h}$$
$$R_e \text{ (Reynolds No.)} = D\bar{V}\rho/\alpha$$
$$= \frac{0.134 \text{ ft} \times 6246 \text{ ft/h} \times 62.4 \text{ lb}_m/\text{ft}^3}{2.42 \text{ lb}_m/\text{ft/h}}$$
$$= 21581 \text{ or } f = 0.006$$

$$H_f = \frac{4 f \bar{V}^2 L}{2 gcD}$$

$$= \frac{4 \times 0.006 \times (1.74 \text{ ft/s})^2 \times 1 \text{ ft}}{2 \times 32.2 \frac{\text{ft lb}_m}{\text{lb}_f - \text{s}^2} \times 0.134 \text{ ft}}$$

$$= 8.42\text{E-3 ft/lb}_f/\text{lb}_m$$

$$P = 8.42\text{E-3} \frac{\text{ft/lb}_f}{\text{lb}_m} \times (500 \times 11) \frac{\text{lb}_m}{\text{h}} \times 3.777\text{E-7} \frac{\text{kWh}}{\text{ft/lb}_f}$$

$$= 1.75\text{E-5 kW/ft of pipe}$$

If the length between measurement points across the water load are within 1 foot and the total power is on the order of 10 kW then:

$$(\Delta P)/P = 1.75\text{e-5}/10 = 1.75\text{e-6 or } 0.00002\%$$

2. Thermal losses. Assume a condition of 50°C heat loss to surrounding at 0°C for both radiation and conduction-convection with a loss of 2 B/ft²/h°R for conduction-convection, and for radiation a black-body in large surroundings.

$$T_H = 50°\text{C} = 323 \text{ K} = 581°\text{R}$$

$$T_C = 0°\text{C} = 273 \text{ K} = 491°\text{R}$$

and

$$g/A = 1728\text{E-12} \frac{B}{\text{ft}^2/\text{h}/°\text{R}^4} [(581°\text{R})^4 - (491°\text{R})^4]$$

$$+ \frac{B}{\text{ft}^2/\text{h}°\text{R}} [581°\text{R} - 491°\text{R}] = 276 \frac{B}{\text{ft}^2/\text{h}}$$

or

$$276 \frac{B}{\text{ft}^2/\text{h}} \times 0.00293 \frac{\text{kWh}}{B} = 0.08 \text{ kW/ft}^2$$

Using a typical area of 0.1 ft² for the water load, the error due to this source is:

$$(\Delta P)/P = 0.008/10 = 0.0008 \text{ or about } 0.1\%$$

Conducted losses can further be reduced by control of the cooling flow to the waveguide next to the water load so that the waveguide is at the same temperature as the load.

IV. Experimental Results

Several test runs were made on a 20 kW X-band (7.190 GHz) klystron, comparing the DC power calculated by the product of the beam voltage and current (with no drive) to the power calculated from the flow and ΔT across the tube collector. Figure 2 is a graph of the measured collector power vs. time. Figure 3 shows the temperature of the coolant entering and leaving the collector, and Fig. 4 is a detail of the percent difference between the two measurement methods. Although the absolute calibration of the DC power measurement is no better than 2%, two important features may be noted:

(1) A change in beam power introduces a transient error in the thermal measurement until the temperature stabilizes.

(2) Even when the beam power is constant, the error still shows some residual temperature effects. In the period from 15 to 23 minutes while the DC power is constant at about 52 kW, the inlet temperature rises about 5 deg C and there is a small drift in the percent difference. At low DC power and with large temperature differences, the effect is larger. While the periods just before 5 minutes and just after 25 minutes are both at about 7 kW DC, the inlet temperature has increased by about 15 deg C and the change in percent difference is over 2%.

V. Conclusions

(1) Thermal measurements offer a theoretical potential for a substantial increase in the accuracy of RF power calibration.

(2) Additional benefits can be achieved by better modeling of the fluid, particularly by integrating the specific heat over the temperature span.

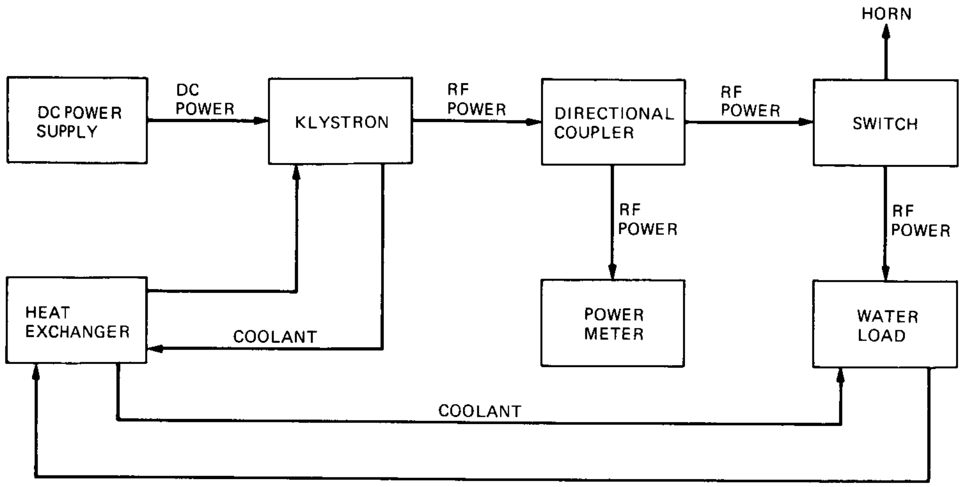

Fig. 1. Simplified transmitter block diagram

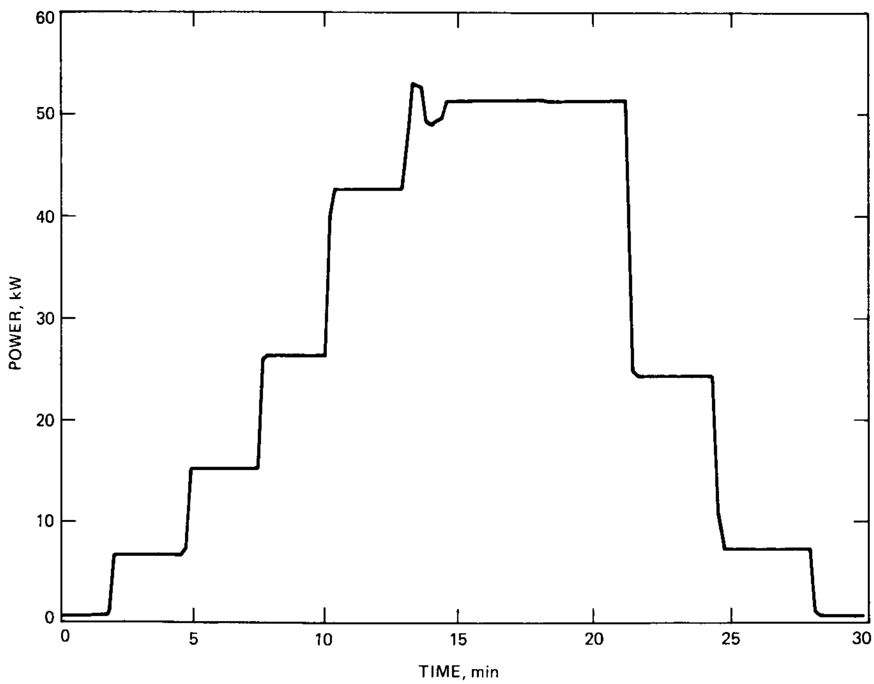

Fig. 2. DC beam power vs time

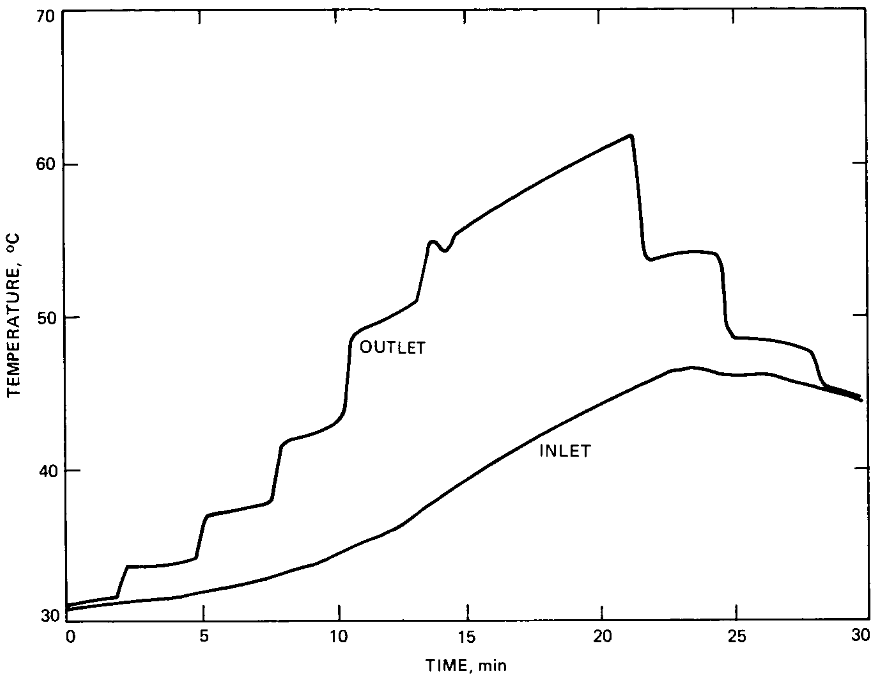

Fig. 3. Inlet and outlet coolant temperature

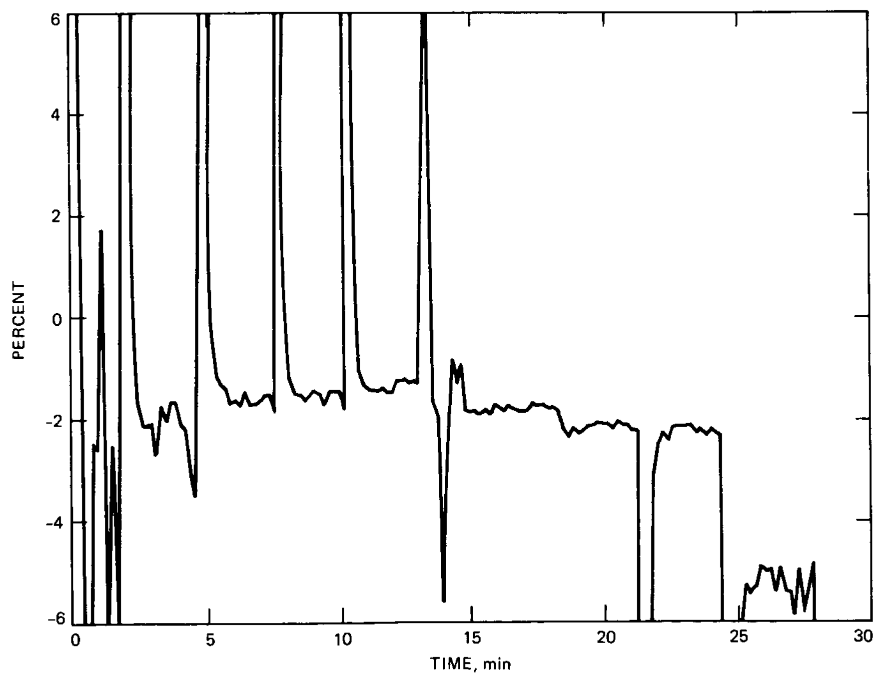

Fig. 4. Percent difference between DC measurement and thermal measurement